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# Higgs Sectors in which the only light Higgs boson is CP-odd and Linear Collider Strategies for its Discovery

Tom Farris<sup>1</sup>, John F. Gunion<sup>1</sup>, Heather E. Logan<sup>2</sup>

<sup>1</sup>Davis Institute for HEP, U. of California, Davis, CA

<sup>2</sup>Fermilab, Batavia, IL

## Abstract

We survey techniques for finding a CP-odd Higgs boson,  $A^0$ , at the Linear Collider that do not depend upon the presence of other light Higgs bosons. The potential reach in  $[m_{A^0}, \tan \beta]$  parameter space for various production/discovery modes is evaluated and regions where discovery might not be possible at a given  $\sqrt{s}$  are delineated. We give, for the first time, results for  $e^+e^- \rightarrow \nu\bar{\nu}A^0$  one-loop  $W$  boson fusion production.

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# Higgs Sectors in which the only light Higgs boson is CP-odd and Linear Collider Strategies for its Discovery

Tom Farris<sup>1</sup>, John F. Gunion<sup>1</sup> and Heather E. Logan<sup>2</sup>

<sup>1</sup>*Department of Physics,  
University of California, Davis, CA 95616*

<sup>2</sup>*Fermilab, Batavia, IL 60510*

We survey techniques for finding a CP-odd Higgs boson,  $A^0$ , at the Linear Collider that do not depend upon the presence of other light Higgs bosons. The potential reach in  $[m_{A^0}, \tan \beta]$  parameter space for various production/discovery modes is evaluated and regions where discovery might not be possible at a given  $\sqrt{s}$  are delineated. We give, for the first time, results for  $e^+e^- \rightarrow \nu\bar{\nu}A^0$  one-loop  $W$  boson fusion production.

A general two-Higgs-doublet model (2HDM) or more complicated extension of the one-doublet Higgs sector of the Standard Model (SM) remains an attractive possibility [1], especially as an effective theory in the context of models with new physics at an energy scale significantly below the usual GUT scale. Although gauge coupling unification is not necessarily relevant in such theories, it can be achieved [2]. For example, for two doublets and one  $T = 1, Y = 0$  triplet, the gauge couplings unify at  $1.6 \times 10^{14}$  GeV; increasingly complicated Higgs sectors are required for gauge coupling unification at still lower scales. (The unification at low scales cannot be true gauge group unification without encountering problems with proton decay. However, there are examples of theories (for example, many string theories) in which the couplings are predicted to unify without the presence of a larger gauge group.) If there is a neutral member of a triplet representation,  $\rho = m_W/(m_Z \cos \theta_W) = 1$  remains natural provided it has zero vev [3].

Current data provide some important hints and constraints regarding the Higgs sector [4]. As is well known, the simplest interpretation of the precision electroweak data is the existence of a rather light SM-like Higgs boson (the mass corresponding to the smallest  $\chi^2$  being  $\sim 88$  GeV, well below the LEP experimental lower limit of 114.1 GeV). However, alternative fits to the precision electroweak data without a light SM-like Higgs boson are possible when an extended Higgs sector is present. We will focus on the CP-conserving (CPC) 2HDM with its five physical Higgs bosons,  $h^0, H^0, A^0, H^\pm$ .

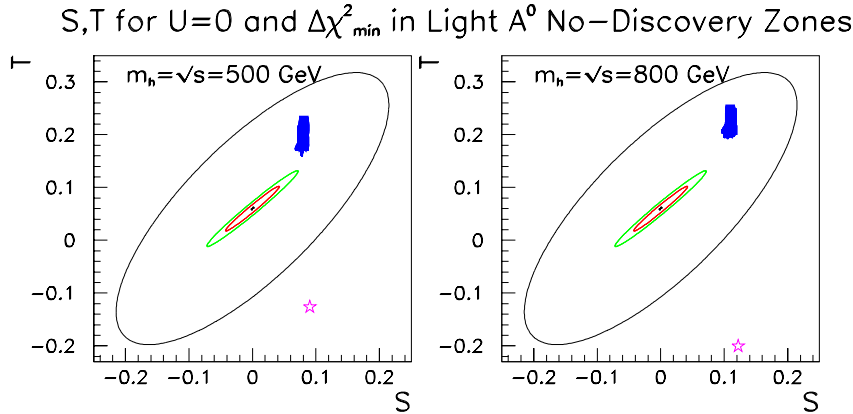


FIG. 1: The outer ellipses show the 90% CL region from current precision electroweak data in the  $S, T$  plane for  $U = 0$  relative to a central point defined by the SM prediction with  $m_{h_{\text{SM}}} = 115$  GeV. The blobs of points show the  $S, T$  predictions for 2HDM models with a light  $A^0$  and with  $\tan \beta$  such that the  $A^0$  cannot be detected in  $b\bar{b}A^0$  or  $t\bar{t}A^0$  production at either the LC or the LHC; the mass of the SM-like  $h^0$  is set equal to  $\sqrt{s} = 500$  GeV (left) or 800 GeV (right) and  $m_{H^\pm}$  and  $m_{H^0}$  have been chosen to minimize the  $\chi^2$  of the full precision electroweak fit. The innermost (middle) ellipse shows the 90% (99.9%) CL region for  $m_{h_{\text{SM}}} = 115$  GeV after Giga- $Z$  LC operation and a  $\Delta m_W \lesssim 6$  MeV threshold scan measurement. The stars to the bottom right show the  $S, T$  predictions in the case of the SM with  $m_{h_{\text{SM}}} = 500$  GeV (left) or 800 GeV (right). This figure is from [6].

The scenario we wish to consider is that in which the  $A^0$  of the 2HDM is light and all other Higgs bosons are heavy. It turns out that this type of scenario can be consistent with precision electroweak constraints [5]. If  $m_{A^0}$  is small, the best fit to the precision electroweak data is achieved by choosing the lighter CP-even Higgs

boson,  $h^0$ , to be SM-like. A good fit is achieved even for  $m_{h^0} \sim 1$  TeV. Of course, such a heavy SM-like  $h^0$  leads to large  $\Delta S > 0$  and large  $\Delta T < 0$  contributions, which on their own would place the  $S, T$  prediction of the 2HDM model well outside the current 90% CL ellipse — see the stars in Fig. 1 (from [6]). However, the large  $\Delta T < 0$  contribution from the SM-like  $h^0$  can be compensated by a large  $\Delta T > 0$  from a small mass non-degeneracy (weak isospin breaking) of the still heavier  $H^0$  and  $H^\pm$  Higgs bosons. In detail, for a light  $A^0$  and SM-like  $h^0$  one finds

$$\Delta\rho = \frac{\alpha}{16\pi m_W^2 c_W^2} \left\{ \frac{c_W^2}{s_W^2} \frac{m_{H^\pm}^2 - m_{H^0}^2}{2} - 3m_W^2 \left[ \log \frac{m_{h^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{s_W^2} \log \frac{m_W^2}{m_Z^2} \right] \right\} \quad (1)$$

from which we see that the first term can easily compensate the large negative contribution to  $\Delta\rho$  from the  $\log(m_{h^0}^2/m_W^2)$  term. In Fig. 1, the blobs correspond to 2HDM parameter choices for which: (a)  $m_{h^0} = \sqrt{s}$  of a linear  $e^+e^-$  collider (LC) (*i.e.*  $m_{h^0}$  is such that the  $h^0$  cannot be observed at the LC); (b)  $m_{H^\pm} - m_{H^0} \sim \text{few GeV}$  has been chosen (with both  $m_{H^\pm}, m_{H^0} \gtrsim 1$  TeV) so that the  $S, T$  prediction is well within the 90% CL ellipse of the current precision electroweak fits; and (c)  $m_{A^0}$  and  $\tan\beta$  are in the ‘wedge’ of  $[m_{A^0}, \tan\beta]$  parameter space for which detection of the  $A^0$  via  $t\bar{t}A^0$  and  $b\bar{b}A^0$  production at the LHC and LC would be difficult [7]. (This wedge will be discussed in more detail below. For  $\sqrt{s} = 1$  TeV and  $L = 1000 \text{ fb}^{-1}$  at the LC,  $m_{A^0}$  values as low as roughly 100 GeV could still fall into this wedge for  $\tan\beta \sim 5$ .) However, this scenario can only be pushed so far. In order to maintain perturbativity for all the Higgs self couplings, it is necessary that the  $h^0, H^0$  and  $H^\pm$  masses not be greatly in excess of 1 TeV. This implies, in particular, that the SM-like  $h^0$  would be detected at the LHC. If it should happen that a heavy SM-like Higgs boson is detected at the LHC, the precision electroweak situation could only be resolved by Giga-Z operation and a  $\Delta m_W = 6$  MeV  $WW$  threshold scan at the LC (with the resulting ellipse sizes illustrated in Fig. 1). The resulting determination of  $S, T$  would be sufficiently precise to definitively check for values like those of the blobs of Fig. 1. If no other new physics was detected at the LC or LHC that could cause the extra  $\Delta T > 0$ , searching for the other Higgs bosons of a possible 2HDM Higgs sector, especially a possibly light decoupled  $A^0$ , would become a high priority.

Interestingly, a light  $A^0$  with  $m_{A^0} \gtrsim 10$  GeV would yield a positive contribution to the muon’s anomalous magnetic moment,  $a_\mu$ , coming mainly from the two-loop Bar-Zee graph [8, 9]. Recent data [10] suggests the presence of just such a deviation from SM expectations. However, after including the recent corrections to the sign of the light-by-light scattering contribution and allowing for uncertainty in  $\sigma_{\text{had}}$ , the discrepancy between the experimental result and the SM prediction is not large, and may not be present at all. The best that can be said is that a small positive discrepancy in  $a_\mu$  can be explained by the presence of an  $A^0$  for moderate values of  $m_{A^0}$  and  $\tan\beta$  in the ‘wedge’ region for which direct discovery of the  $A^0$  would be difficult at the LC and LHC using the standard modes we describe later.

To summarize, it is not unreasonable to suppose that the Higgs sector contains a 2HDM with a light  $A^0$ , a heavy SM-like  $h^0$ , and still heavier  $H^0$  and  $H^\pm$  with a small mass splitting. The  $h^0$  would be detected at the LHC, but we would have no understanding of how this is to be made consistent with precision electroweak constraints. Direct detection of the  $A^0$  would become a priority. In the remainder of this note, we wish to consider the various means for detecting a light  $A^0$  at a linear collider.

At the LC, the relevant discovery processes for a  $A^0$  with no tree-level  $WW, ZZ$  couplings are:  $e^+e^- \rightarrow t\bar{t}A^0$  and  $e^+e^- \rightarrow b\bar{b}A^0$  [11, 12] [7];  $e^+e^- \rightarrow Z^* \rightarrow ZA^0A^0$  [13];  $e^+e^- \rightarrow \nu\bar{\nu}W^*W^* \rightarrow \nu\bar{\nu}A^0A^0$  [14];  $\gamma\gamma \rightarrow A^0$  [15] (see also [16]). That these processes might have reasonable rates follows from the couplings involved. At least one of the  $\gamma_5$  Yukawa couplings of the  $A^0$  must be substantial: relative to SM-like strength,  $t\bar{t}A^0 = \cot\beta$  and  $b\bar{b}A^0 = \tan\beta$ . The quartic couplings,  $ZZA^0A^0$  and  $W^+W^-A^0A^0$ , arise from the gauge covariant structure  $(D_\mu\Phi)^\dagger(D^\mu\Phi)$  and are of guaranteed magnitude. The  $\gamma\gamma \rightarrow A^0$  coupling derives from fermion loops, and, as noted, not both the  $b\bar{b}A^0$  and  $t\bar{t}A^0$  coupling can be suppressed.

Turning first to  $t\bar{t}A^0$  and  $b\bar{b}A^0$  production, the former (latter) always yields significant rates if  $\tan\beta$  is small (large) enough (and the process is kinematically allowed). But, even for high  $\sqrt{s}$  and large luminosity, there remains a wedge of moderate  $\tan\beta$  for which neither process provides adequate event rate [7, 12]. The wedge corresponding to fewer than 20 events in either process for  $L = 1000 \text{ fb}^{-1}$  at  $\sqrt{s} = 800$  GeV is shown in Fig. 2. (Probably backgrounds would imply that more than 20 events would be needed to see the signal, so this wedge is a conservative indication of the region in which these processes would not be visible.) The extent of the corresponding wedge at the LHC can be estimated from the CMS and ATLAS [17, 18]  $[m_{A^0}, \tan\beta]$  discovery region plots for the MSSM Higgs sector as follows. At high  $\tan\beta$ , the  $b\bar{b}H^0$  and  $b\bar{b}A^0$  processes make roughly equal contributions to the  $b\bar{b}\tau^+\tau^-$  final state signal. Since the rates are proportional to  $\tan^2\beta$ , the location of the upper limit of the LHC wedge simply needs to be rescaled by a factor of  $\sqrt{2}$ , implying the LHC could find a  $A^0$  signal for  $\tan\beta > 14$  at  $m_{A^0} = 250$  GeV (comparable to the LC result) rising to  $\tan\beta > 24$  at  $m_{A^0} = 500$  GeV (which is significantly better coverage than the LC). However, at low  $\tan\beta$ , the only MSSM channel for  $A^0$  discovery at the LHC deemed viable to date employs  $A^0 \rightarrow Zh^0$  decays which would be absent in the type of model being considered here in which only the  $A^0$  is light.

### Viability Regions for 2HDM $t\bar{t}A$ , $b\bar{b}A$ , $\nu\nu AA$ and $\gamma\gamma \rightarrow A$ Signals

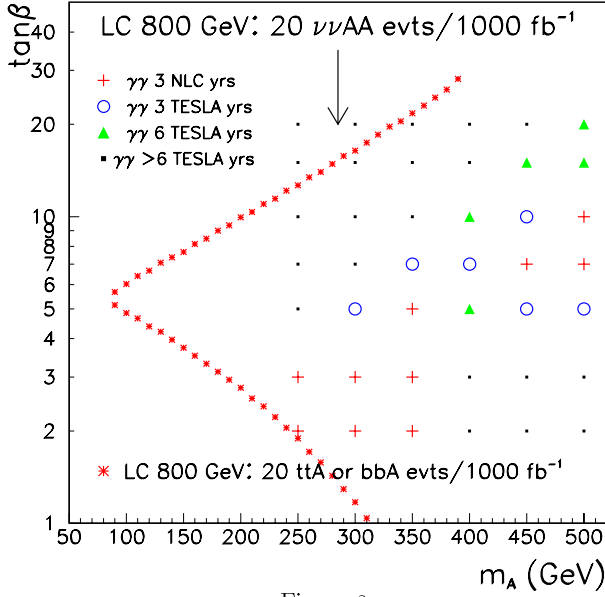


Figure 2

### Cross Sections for $e^+e^- \rightarrow ZAA$ and $\nu\nu AA$

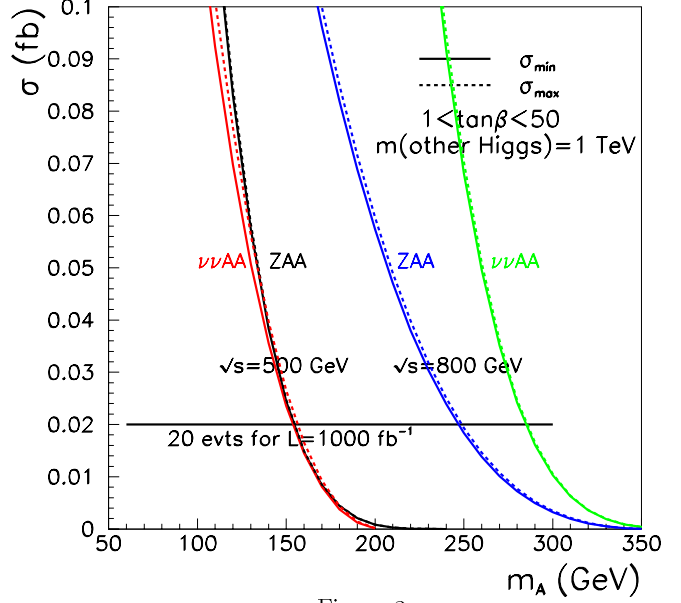


Figure 3

FIG. 2: We display (using stars) the wedge of  $[m_{A^0}, \tan \beta]$  parameter space inside which a LC operating at  $\sqrt{s} = 800$  GeV yields fewer than 20 events per 1000  $\text{fb}^{-1}$  in both the  $t\bar{t}A^0$  and  $b\bar{b}A^0$  production modes. Also shown by the arrow is the  $m_{A^0}$  value above which the process  $e^+e^- \rightarrow \nu\bar{\nu}A^0A^0$  yields fewer than 20 events per 1000  $\text{fb}^{-1}$ . The + symbols on the grid of  $[m_{A^0}, \tan \beta]$  values show the points for which a  $4\sigma$  signal for  $\gamma\gamma \rightarrow A^0$  would be achieved using NLC operation at  $\sqrt{s} = 630$  GeV after three  $10^7$  sec years of operation assuming running conditions and strategies as specified in [15]. In particular, operation for two years using a polarization configuration for the electron beams and laser photons yielding a broad  $E_{\gamma\gamma}$  spectrum and one year using a configuration yielding a peaked spectrum is assumed. The circles (triangles) show the additional points that would yield a  $4\sigma$  signal for twice (four times) the integrated luminosity of the current NLC  $\gamma\gamma$  interaction region design. The factor of two increase is probably attainable at TESLA. The small squares show the additional points sampled in the study of [15].

FIG. 3: We plot the cross sections for  $e^+e^- \rightarrow Z^*A^0A^0$  and  $e^+e^- \rightarrow \nu\bar{\nu}A^0A^0$  as a function of  $m_{A^0}$ , assuming a 2HDM model with a heavy SM-like  $h^0$ . We have taken  $m_{h^0} = m_{H^0} = m_{H^\pm} = 1$  TeV. Maximum and minimum values found after scanning  $1 \leq \tan \beta \leq 50$  are shown for  $\sqrt{s} = 500$  GeV and 800 GeV. (The variation with  $\tan \beta$  arises from small contributions associated with exchanges of the heavy Higgs bosons.) The 20 event level for  $L = 1000 \text{ fb}^{-1}$  is indicated.

For the lower values of  $m_{A^0}$ , double Higgs production via the quartic couplings will allow discovery at the LC even in the wedge region. The cross sections for  $e^+e^- \rightarrow Z^* \rightarrow Z^0A^0A^0$  and  $e^+e^- \rightarrow \nu\bar{\nu}A^0A^0$  are shown in Fig. 3. For instance, the process  $e^+e^- \rightarrow Z^* \rightarrow Z^0A^0A^0$  yields 20 events for  $L = 1000 \text{ fb}^{-1}$  for  $m_{A^0} \lesssim 160$  GeV ( $m_{A^0} \lesssim 250$  GeV) for  $\sqrt{s} = 500$  GeV ( $\sqrt{s} = 800$  GeV), while  $WW \rightarrow A^0A^0$  fusion production yields 20 events for  $m_{A^0} \lesssim 160$  GeV ( $m_{A^0} \lesssim 290$  GeV), respectively. A careful assessment of backgrounds is required to ascertain just what the mass reach of these processes actually is.

If the  $\gamma\gamma$  collider option is implemented at the LC,  $\gamma\gamma \rightarrow A^0$  will provide a signal for a decoupled  $A^0$  over a significant portion of the wedge region. The results from the quite realistic study of [15] are illustrated in Fig. 2, which focuses on  $m_{A^0} \geq 250$  GeV. The pluses indicate  $4\sigma$  discovery points after 3 years of appropriate running at the NLC. The higher TESLA luminosity for  $\gamma\gamma$  collisions would allow  $4\sigma$  discovery for the additional points indicated by the circles.

Finally, although we don't present details here, a muon collider capable of operating at  $\sqrt{s} = 500$  GeV and below would probably be able to provide  $4\sigma$  signals for the  $A^0$  in the  $m_{A^0} < 500$  GeV wedge region after about 3 years of appropriately configured operation, assuming the current nominal Higgs factory luminosities. For more details, see [19].

The above results indicate the need for exploring additional mechanisms by which a  $A^0$  with  $m_{A^0} \geq 250$  GeV might be produced and detected. The remaining possibilities are the one-loop processes:  $e^+e^- \rightarrow \gamma A^0$ ,  $e^+e^- \rightarrow Z A^0$  and  $e^+e^- \rightarrow \nu\bar{\nu}A^0$ . The first two have previously been explored in [20, 21]. Results for the third process will be given for the first time here; details of the computation will appear in [22]. The results we shall present for  $e^+e^- \rightarrow \gamma A^0$  agree (where comparison is possible) with the 2HDM results of [20], but not with those of [21]. Our results for  $e^+e^- \rightarrow Z A^0$  do not agree except in a very rough way with the 2HDM results of [21]. (The  $e^+e^- \rightarrow Z A^0$  process was not computed in [20].) In all our loop computations, we have employed the running  $b$ -quark mass as a function of  $m_{A^0}$  in evaluating the  $b\bar{b}A^0$  coupling employed in computing the  $b$ -quark

loop contribution to the one-loop couplings. Our results are obtained by including only the fermion  $b, t$  loop contributions; in particular, we assume that all other Higgs bosons are sufficiently heavy that loop diagrams containing them will be small.

Our results for  $e^+e^- \rightarrow \gamma A^0$ ,  $ZA^0$  and  $\nu\bar{\nu}A^0$  appear in the three windows of Fig. 4. From these figures, it should be immediately clear that the only process that might yield a useful event rate is  $e^+e^- \rightarrow \gamma A^0$ , and then only if  $\tan\beta$  is not large. For  $e^+e^- \rightarrow \gamma A^0$ , roughly 80 declining to 30 events are predicted for  $\tan\beta = 1$  and  $m_{A^0} = 20$  GeV increasing to 350 GeV, assuming  $\sqrt{s} = 500$  GeV and  $L = 1000$  fb $^{-1}$ . At  $\tan\beta = 5$ , only 3 declining to 1 events are anticipated for the same  $m_{A^0}$  mass range. Unfortunately, there will be substantial background. Assuming that the search will take place in the  $\gamma b\bar{b}$  final state, the irreducible background will come from  $e^+e^- \rightarrow \gamma b\bar{b}$  production. This was evaluated in [23]. The result found is  $d\sigma/dm_{b\bar{b}} = 0.5$  fb/(10 GeV) [0.2 fb/(10 GeV)] at  $m_{b\bar{b}} = 200$  GeV [400 GeV] at  $\sqrt{s} = 500$  GeV. Even if an optimistic mass resolution of  $\Delta m_{b\bar{b}} = 5$  GeV can be achieved, we see that this irreducible background will be at the level of 250 to 100 events in the indicated mass range. In addition, other backgrounds as well as efficiencies for tagging and event selection must be taken into account. Thus, our conclusion is that the one-loop processes are unlikely to provide a measurable signal, and certainly cannot be used as discovery modes, unless  $\tan\beta < 1$ .

In conclusion, there are a variety of perfectly viable Higgs sector models in which it would be highly desirable to be able to detect a relatively light CP-odd  $A^0$  without relying on associated production with other Higgs bosons. Such detection might be crucial to determining the nature of the Higgs sector but may be quite difficult. A linear  $e^+e^-$  collider, including the  $\gamma\gamma$  collider option, provides the best range of possibilities for  $A^0$  discovery. Even when the  $e^+e^- \rightarrow \nu\bar{\nu}A^0A^0$  pair process becomes strongly kinematically suppressed (roughly  $\sqrt{s} < 200$  GeV +  $2m_{A^0}$ ),  $\gamma\gamma \rightarrow A^0$  production continues to provide an opportunity for  $A^0$  discovery in the moderate- $\tan\beta$  ‘wedge’ region of  $[m_{A^0}, \tan\beta]$  parameter space where  $t\bar{t}A^0$  and  $b\bar{b}A^0$  production both fail. Although this will still leave some portions of  $[m_{A^0}, \tan\beta]$  parameter space inaccessible to  $A^0$  discovery, it is quite impressive that the tools and techniques that have been developed for Higgs detection at the LC have reached a high enough level of sophistication that we should have a good chance of detecting and studying the Higgs bosons of even rather unusual Higgs sectors.

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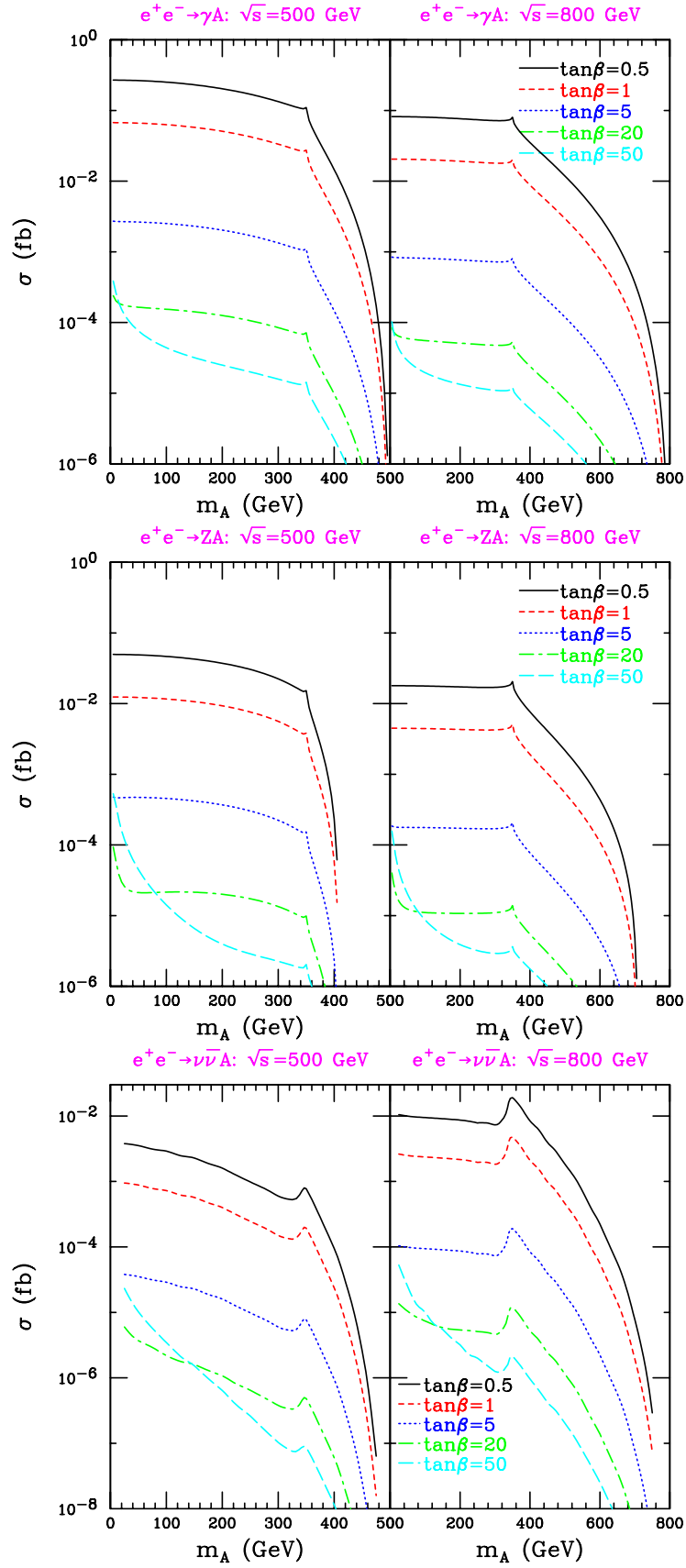


FIG. 4: The  $e^+e^- \rightarrow \gamma A^0$ ,  $ZA^0$  and  $\nu\bar{\nu}A^0$  cross sections as a function of  $m_{A^0}$  for  $\sqrt{s} = 500$  GeV and 800 GeV, for  $\tan\beta = 0.5, 1, 5, 20, 50$ .